

Status of CMB Polarization Measurements from DASI and Other Experiments

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ABSTRACT

We review the current status and future plans for polarization measurements of the cosmic microwave background radiation, as well as the cosmology these measurements will address. After a long period of increasingly sensitive upper limits, the DASI experiment has detected the E -mode polarization and both the DASI and WMAP experiments have detected the TE correlation. These detections provide confirmation of the standard model of adiabatic primordial density fluctuations consistent with inflationary models. The WMAP TE correlation on large angular scales provides direct evidence of significant reionization at higher redshifts than had previously been supposed. These detections mark the beginning of a new era in CMB measurements and the rich cosmology that can be gleaned from them.

1. Introduction

Tremendous progress has been made in characterizing the angular power spectrum of the CMB temperature fluctuations over the last decade. As discussed extensively at the workshop, the temperature anisotropy spectrum is now well-determined from the largest angular scales through the first two acoustic peaks and into the third at $\ell \sim 700$. Data on smaller angular scales, in particular from the CBI and ACBAR experiments, have revealed the damping tail of the primordial spectrum (Runyan et al. 2003; Mason et al. 2002; Kuo et al. 2002). The high- ℓ data provide evidence for the onset of secondary anisotropy at $\ell \sim 2000$ that is also detected at $\ell \sim 5000$ with BIMA (Dawson et al. 2001), and that presumably arises at least in part from the integrated Sunyaev-Zel'dovich Effect from galaxy clusters (e.g., Komatsu & Seljak 2002; Holder 2002). Future cosmological studies with the CMB will therefore focus on measurement of the temperature anisotropy at fine angular scales and on the polarization anisotropy at all scales. This paper concentrates on the latter.

Measurements of astronomical polarization are in general difficult and the low level of the CMB polarization signal makes it an especially challenging target. Yet the fundamental nature

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of the science has fueled rapid progress in experimental efforts to reach unprecedented levels of sensitivity and control of systematics. The following is an abbreviated list of the scientific goals of CMB polarization studies, ranked in increasing order of required instrumental sensitivity:

1. Test the theoretical framework for the generation of CMB anisotropy: Within the context of the standard model, in which peaks in the CMB angular power spectrum are interpreted as the signature of acoustic oscillations seeded by nearly scale-free, primordial adiabatic density fluctuations, current temperature measurements lead to highly-specific predictions for the shape of the polarization power spectrum. Furthermore, it is a firm prediction that density fluctuations should create only E -mode, i.e., curl-free, polarization patterns on the sky (see § 2).
2. Determine the reionization history of the universe: When the universe underwent reionization, electrons re-scattered the CMB, leading to polarization on the large angular scales corresponding to the horizon size at the epoch of reionization.
3. Improve the precision of CMB-derived cosmological parameters: Polarization accounts for two thirds of the CMB observables permitting higher precision constraints, and also allows various parameter degeneracies to be broken.
4. Provide a probe of large-scale structure to $z = 1100$. Gravitational lensing of the CMB by intervening structure distorts the polarization pattern generated at the surface of last scattering, leading to an observable B -mode, i.e., curl component. The B -mode, although weak, should be detectable and can be used to infer properties of the large-scale structure (Hu & Okamoto 2002).
5. Test inflation by searching for primordial gravitational waves: Primordial gravity waves will lead to polarization in the CMB (Polnarev 1985; Crittenden et al. 1993) with both an E -mode pattern, as for the scalar density perturbations, and a B -mode pattern, due to the intrinsic polarization of the gravitational waves (Seljak 1997; Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997). In inflationary models, the amplitude of the B -mode polarization from gravity waves is proportional to the fourth power of the inflationary energy scale. While the detection of B -mode polarization would provide a critical test of inflation, the signal may be so weak as to be unobservable (Lyth 1997; Kinney 2003).

The current state of CMB polarization studies is similar to the state of temperature measurements a decade ago, when COBE and FIRS had detected anisotropy (Smoot et al. 1992; Ganga et al. 1993), but much work remained to be done to characterize its power spectrum. Currently, DASI has detected the E -mode polarization and TE correlation on degree scales (Kovac et al. 2002), while WMAP has detected the TE correlation on large scales (Kogut et al. 2003; Kogut 2003). The degree-scale polarization and the TE correlation are critical tests of the underlying theoretical framework for the generation of CMB fluctuations, while the WMAP TE correlation on

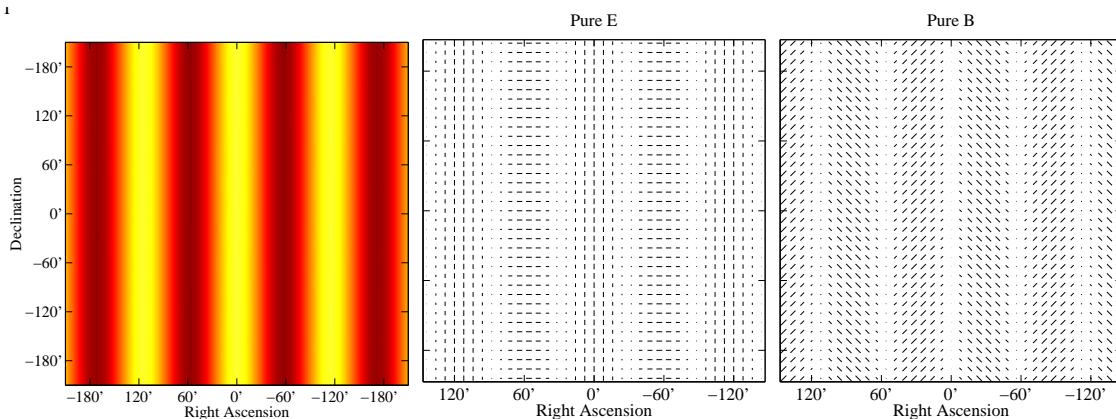


Fig. 1.— E and B -mode polarization patterns. (left panel) A representative Fourier mode of a density perturbation. (middle) E -mode polarization pattern resulting from Thomson scattering of this mode (growing amplitude). (right) B -mode polarization pattern.

very large scales, i.e., the first several multipoles, provides direct evidence of significant reionization at higher redshifts than had previously been supposed.

In this contribution, we first briefly review the mechanism which causes observable polarization within the context of adiabatic density perturbations, lensing by large-scale structure and gravity waves. We next review the history of polarization measurements, the DASI and WMAP detections (particular emphasis is given to the DASI experiment as the WMAP results are also discussed in contributions by Wright (2003) and Kogut (2003)), several upcoming and future experiments, and conclude with a few remarks on the state of the field.

2. Generation of CMB Polarization

Polarization of the CMB arises from Thomson scattering of the background radiation off electrons at the epoch of decoupling (Rees 1968). As scattering can only produce a net polarization if an electron sees a local quadrupole moment, polarization is suppressed as long as the photon mean free path is short, and electrons see a field that is locally uniform. As recombination proceeds, however, the mean free path grows rapidly and electrons begin to see radiation Doppler-shifted by velocity fields within the plasma.

To illustrate this effect, consider a single spatial mode of the density field, i.e., a standing acoustic wave; as the amplitude of the wave oscillates, the photon-baryon fluid will compress and expand. If the mode is growing, the fluid will move toward density crests. In this case, the radiation field seen by electrons near a crest is Doppler-boosted perpendicular to the crest, with no boost seen parallel to the crest, leading to scattered light whose polarization is aligned with the crest.

Likewise in the troughs, the radiation is reduced in directions perpendicular to the trough, but uniform along it, and the resulting polarization will be perpendicular to the trough, i.e., the sense of the polarization flips between crest and trough (see Figure 1). If the amplitude of the density mode is decreasing, the sense of the polarization is reversed, but in general, scattering leads to polarization aligned either perpendicular or parallel to the wave vector, a curl-free pattern we refer to as *E*-mode polarization (see also Hu & White 1997; Zaldarriaga & Seljak 1997). The first detection of *E*-modes in the CMB by the DASI experiment is discussed in § 3.2.

We have so far considered a time snapshot of a single density mode; if we now consider the dynamic evolution of that mode, we see that because *E*-mode polarization arises from velocities, the amplitude of the polarization will fall to a minimum at the compression or expansion maxima of the density mode, when the velocity drops to zero. Likewise the amplitude of the polarization will be highest at the density nulls, when the fluid velocity reaches a maximum. As a result, the power spectra of the temperature and polarization fields exhibit peaks which are approximately a half-cycle out of phase (see Figure 2). The *TE* correlation spectrum quantifies the complex relation between these fields, with the sign of the correlation depending on whether the amplitude of the mode was increasing or decreasing at the time of decoupling.

When the universe reionized, late-time Thompson scattering of CMB photons reduced power in the anisotropy at small scales but regenerated a polarized signal on scales comparable to the horizon at the reionization epoch, leading to a significant low- ℓ bump in the *E*-mode and *TE* correlation spectra. Such a signal has now been seen in the *TE* spectrum by the WMAP experiment (see § 3.2).

Any polarization field can be decomposed into curl-free (*E*-mode) components, and pure curl components, called *B*-modes by analogy with electric and magnetic fields. The *B*-type harmonic modes exhibit linear polarization at $\pm 45^\circ$ to the direction of modulation (Figure 1). Such a pattern cannot be produced by density modes, and the presence of *B*-modes in the CMB would be the distinctive signature of gravitational effects. A stochastic background of primordial gravity waves generated by inflation would directly source *B*-modes in the CMB. Because such waves decay after entering the horizon, the spectrum of the resulting *B*-mode signal is expected to peak at large angular scales, with an amplitude that is tied to the (highly uncertain) inflationary energy scale. Within the next decade this signal may be detected yielding exciting direct evidence for inflation, or may be shown to be unobservably small. On small angular scales, *B*-modes are confidently expected from gravitational lensing of the *E*-mode signal by large-scale structure (see Figure 2), at a level that should be detectable by the next generation of dedicated polarimeters (see § 4);

3. Polarization Measurements

Prior to the DASI polarization results discussed below (see Kovac et al. 2002), only upper limits had been placed on the level of CMB polarization, a measure both of the demanding instrumental

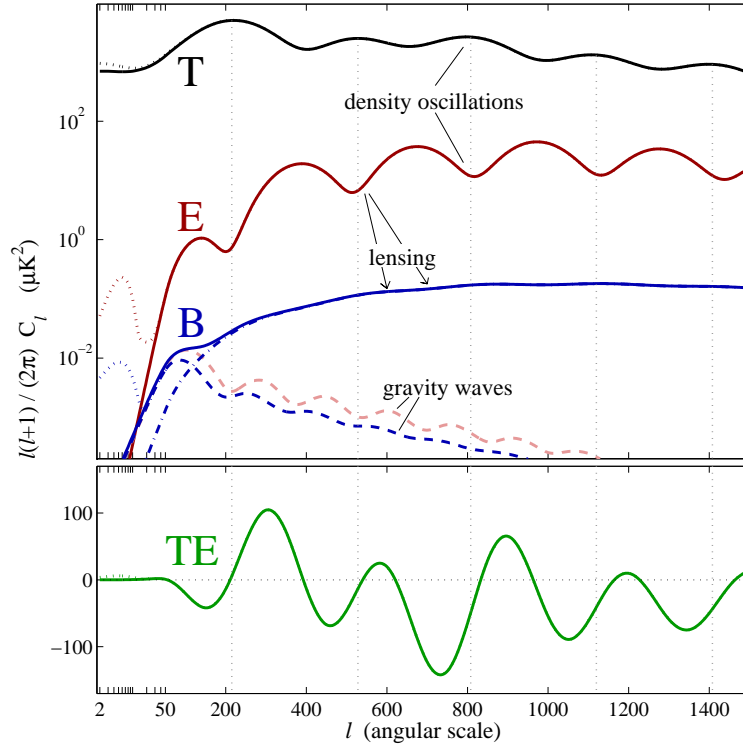


Fig. 2.— Predicted power spectra for the “standard” model. Top to bottom: (*T*) Temperature, (*E*) *E*-mode polarization, (*B*) *B*-mode polarization, and (*TE*) Temperature-*E*-mode cross correlation spectra. The modification of each spectrum resulting from reionization of the magnitude observed by WMAP is shown by the dotted lines. Gravitational waves at a level allowed by current data introduce contributions to the *E*-mode and *B*-mode spectra shown by the dashed lines. The dot-dash line shows the contribution to the *B*-mode signal resulting from lensed *E*-modes. (Spectra calculated using CMBFAST, Seljak & Zaldarriaga 1996).

sensitivity and attention to sources of systematic uncertainty necessitated by the weakness of the expected signal (see Staggs et al. 1999, for a review of CMB polarization measurements). We review these limits below, followed by a discussion of the recent detections of polarization by the DASI and WMAP experiments.

3.1. Early Limits

The first constraint on the degree of polarization of the CMB was placed in 1965 by its co-discoverers Penzias and Wilson, who stated that the new radiation they had detected was isotropic and unpolarized within the limits of their observations (Penzias & Wilson 1965). Over the next 20 years, dedicated polarimeters were used to set much more stringent upper limits on angular scales of several degrees and larger (Caderni et al. 1978; Nanos 1979; Lubin & Smoot 1979, 1981; Lubin

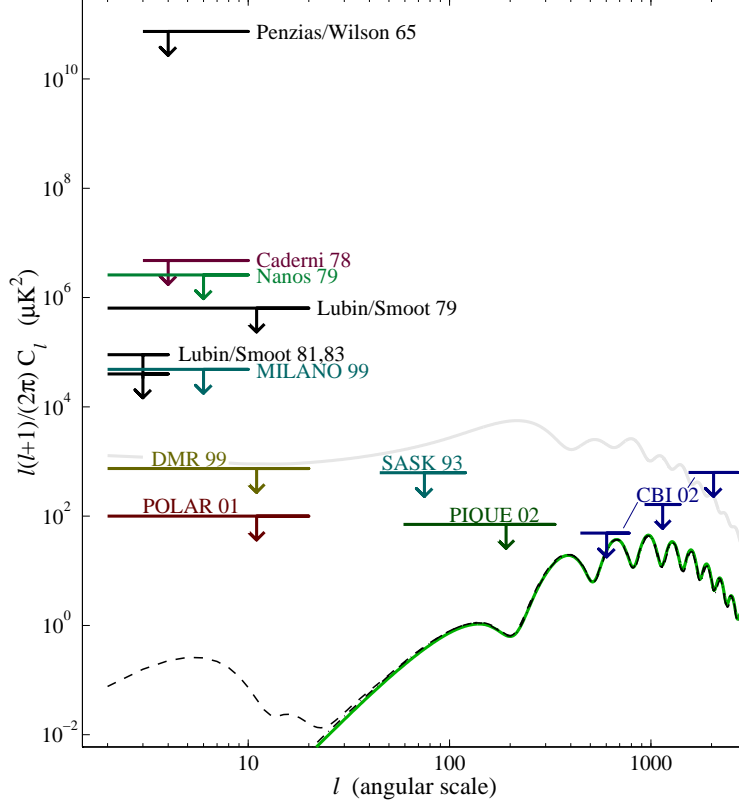


Fig. 3.— Experimental limits to the polarization of the CMB anisotropy prior to the 2002 DASI detection. See text for references.

et al. 1983, see also Sironi et al. 1997), with the best upper limits for the E -mode and B -mode polarizations being $10 \mu\text{K}$ at 95% confidence for the multipole range $2 \leq \ell \leq 20$, from the POLAR experiment (Keating et al. 2001). The POLAR experiment was reconfigured to the COMPASS experiment at intermediate scales (Farese et al. 2003).

An analysis of data from the Saskatoon experiment (Wollack et al. 1993) set the first upper limit on somewhat smaller angular scales ($25 \mu\text{K}$ at 95% confidence for $\ell \sim 75$); this result is also noteworthy for being the first that was below the level of the CMB temperature anisotropy. The best limit on similar angular scales was set by the PIQUE experiment (Hedman et al. 2002) — a 95% confidence upper limit of $8.4 \mu\text{K}$ to the E -mode signal, assuming no B -mode polarization. Analysis of CBI data set upper limits similar to the PIQUE result, but on somewhat smaller scales (Cartwright 2003). An attempt was also made to search for the TE correlation using the PIQUE polarization and Saskatoon temperature data (de Oliveira-Costa et al. 2002).

Polarization measurements have also been pursued on arcminute scales, resulting in several upper limits (e.g., Partridge et al. 1997; Subrahmanyan et al. 2000). However, at these angular scales, corresponding to multipoles ~ 5000 , the level of the primary CMB anisotropy is strongly

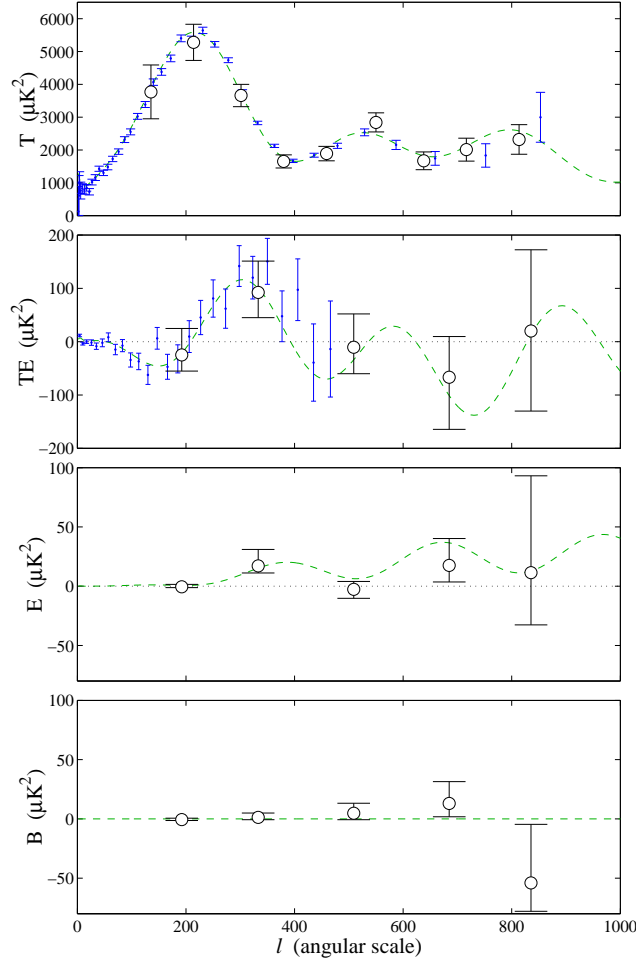


Fig. 4.— Recent detections of CMB polarization with DASI and WMAP. Panels show experimental band-powers of, in order from top to bottom, temperature T , TE correlation, E -mode, and B -mode polarization. DASI points are shown as open circles, WMAP as small closed symbols.

damped and secondary effects due to interactions with large-scale structure in the universe are expected to dominate (Hu & Dodelson 2002).

3.2. Detections

As can be seen in Figure 3, high-resolution experiments have steadily converged on the sensitivity required to see the E -mode signature expected under the standard model. With the results from the DASI experiment, reported in (Kovac et al. 2002, see also Kovac 2003 for details), the goal of direct detection of the E -modes has now been achieved, with the ancillary detection of the TE correlation. More recently, the WMAP experiment has reported the detection of the TE

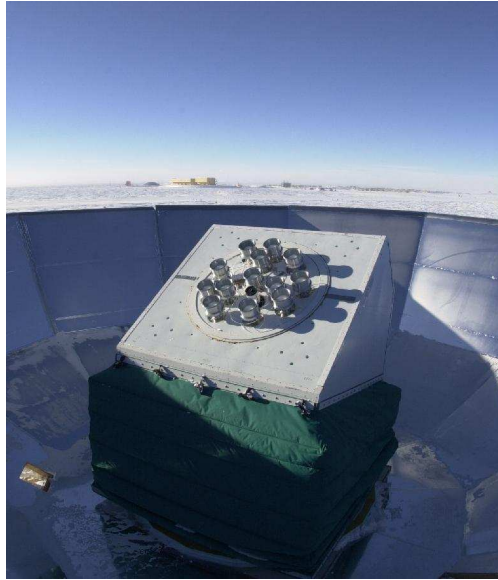


Fig. 5.— DASI in its ground shield, showing the feeds and movable faceplate. The Amundsen-Scott South Pole Station can be seen in the background.

correlation on large-scales. These results are summarized in Figure 4.

The DASI experiment exploits the unique properties of interferometry directly to measure Fourier components of the CMB anisotropy with tight control of systematics. As interferometers are correlating devices, they are largely insensitive to sources of incoherent noise, while providing an effective response on the sky that is a near-perfect Fourier filter (see Figure 6). DASI’s elements are mounted on a faceplate that can be rotated to sample different Fourier modes, or to sample the same modes with independent antennas. DASI was used successfully to measure the temperature anisotropy spectrum during the austral 2000 winter; the design and calibration of the instrument, the power spectrum, and the resulting cosmological constraints are reported in Leitch et al. (2002b), Halverson et al. (2002) and Pryke et al. (2002), respectively. For additional details see Halverson (2002).

The reconfiguration and operation of the instrument for polarization observations are described in detail in Leitch et al. (2002a). During the 2000—2001 austral summer, broadband achromatic polarizers were installed in each of the 26–36 GHz receivers, and a large reflecting screen was erected to reduce the sensitivity to contamination from the ground. By mechanically switching the polarizers for each receiver to pass left (L) or right (R)-circularly polarized light, each baseline (a single pair of antennas whose signals are correlated) can sample the full complement of Stokes parameters, where co-polar (RR & LL) states are sensitive to the total intensity, and cross-polar (RL & LR) states are sensitive to linear polarization (see Figure 6). As can be seen in Figure 7, simple combinations of the cross-polar data produce nearly pure E -mode and B -mode responses on the sky.

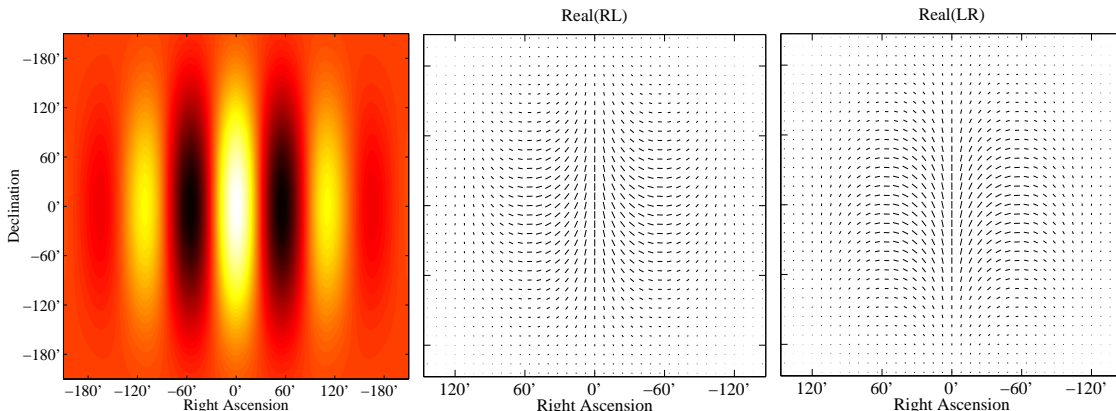


Fig. 6.— Effective response of a single baseline of an interferometer, for total intensity (left panel), and cross-polarized baselines (right panels) (see § 3.2). It can be seen that the intensity response differs from a pure matched Fourier filter only by the taper of the primary beam.

Since the austral summer of 2001, DASI has observed two regions of sky, with a field of view of approximately $3^\circ.4$. A host of consistency tests on the data demonstrate that the combination of shielding, field-differencing and careful characterization of the instrumental polarization has reduced any common-mode residuals to well below the level required to detect CMB polarization, resulting in one of the deepest integrations ever achieved on the CMB. The effective noise on the DASI temperature map of the CMB in these fields is approximately $2.7\mu\text{K}$, and has been demonstrated to integrate down with the square-root of time from timescales of seconds to years.

The DASI data have yielded a direct detection of E -mode polarization; parameterizing the power spectrum as a single shaped bandpower over the full ℓ -range, we find that E -mode polarization is detected at 4.9σ significance, with likelihood ratio tests demonstrating that the data strongly prefer the concordance model shape to flat or power law alternatives. Results with the various power spectra parameterized in five bands are shown in Figure 4. The shape and amplitude of the E -mode spectrum are consistent with predictions from the current best-fit model to the temperature data.

The strategy of very deep integration on a small region of sky yielded not only a statistical detection of polarization with DASI, but a data set containing many high signal-to-noise polarization modes. The temperature map, and the polarization map constructed from these high signal-to-noise modes, are shown in Figure 8.

Both DASI and WMAP (see workshop contributions by Wright (2003) and Kogut (2003)) have also detected the distinctive TE correlation of the CMB, which is a simple consequence of the fact that the fluid velocities which lead to polarization (see § 2) are sourced by the same density fluctuations which lead to temperature anisotropy (second panel of Figure 4). The power of full-sky mapping experiments like WMAP is evident on the largest scales, where the DASI measurement

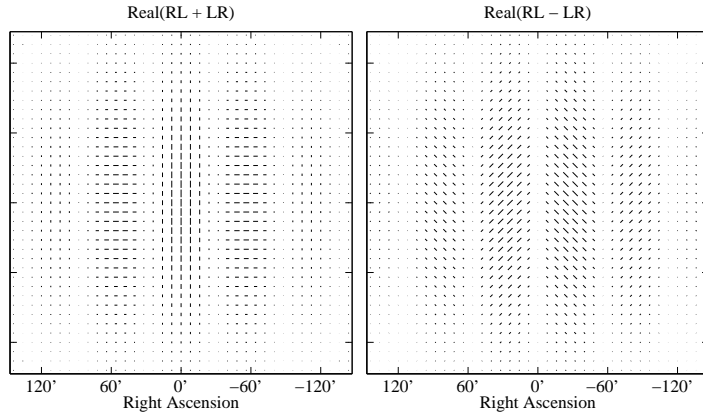


Fig. 7.— Linear combinations of the DASI cross-polar baseline responses shown in Figure 6. It can be seen by comparison with Figure 1 that combinations of $RL \pm LR$ differ from pure E -mode and B -mode responses only by the taper of the primary beam, which results in a tiny and easily-characterized leakage between responses to the two modes (Kovac 2003).

of the TE correlation is limited by sample variance on the temperature signal. The first-year data from WMAP have resulted in confirmation of the predicted large-scale TE correlation, and extraordinary direct evidence of significant reionization at higher redshifts than had previously been supposed (see Figure 9).

4. Ongoing and Upcoming Experiments

4.1. Ongoing Experiments

In addition to DASI and WMAP, both of which are still collecting data, there are several ongoing CMB polarization experiments that have recently obtained data. Like DASI and WMAP they can be classified as second-generation experiments and are likely to result in detections. As second generation experiments they have benefited from the lessons learned from the pioneering experiments discussed in §3.1.

4.1.1. ground-based

Ongoing ground-based experiments include DASI (§3.2), the Cosmic Background Imager (CBI, Padin et al. (2002)) and the Cosmic Anisotropy Polarization Mapper (CAPMAP, Barkats (2003)).

The CBI is a companion instrument to DASI which uses low-noise 26–36 GHz HEMT amplifiers (Pospieszalski & Wollack 2000) and operates from the Atacama plateau in Chile. The thirteen 0.9

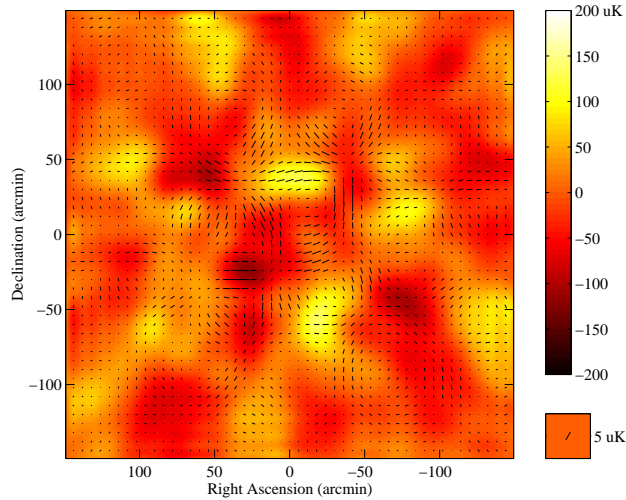


Fig. 8.— Difference map of the two fields observed in the DASI polarization experiment. Grayscale is the temperature map, showing high signal-to-noise detection of CMB structure. Noise in this map is approximately $2.7\mu\text{K}$. Vector overlay is the E -mode polarization map constructed from the high signal-to-noise modes in the data (Kovac 2003).

meter on-axis Cassegrain interferometer elements are mounted on a common Alt-Az platform which also can be rotated along the line of sight. In early 2003, the receivers were fitted with the same selectable achromatic polarizers developed for DASI (Leitch et al. 2002a). Like DASI, each receiver is sensitive to only one circular polarization state and therefore the interferometer is a factor of four slower than optimum. The benefit of this scheme, however, is that the existing 10 GHz bandwidth, 13-element, correlator (Padin et al. 2001) does not need to be expanded. The polarization sensitivity of the CBI expressed in units of temperature is similar to DASI’s but at three times higher angular resolution, i.e., for similar integration time, the CBI should achieve roughly the same polarization sensitivity as DASI in units of $\ell(\ell+1)C_\ell$, but at three times higher ℓ . Scaling from the DASI results shown in Fig. 4, we see that the CBI ℓ -range and sensitivity should be well matched for characterizing the E -mode spectrum.

The CAPMAP experiment, run by Suzanne Staggs and collaborators, uses the radiometers and techniques developed for the PIQUE experiment (§3.1; Hedman et al. (2002)) on the Bell Laboratory 7-meter off-axis telescope. They operated CAPMAP in 2003 February through April with a limited set of four W-band (14 GHz bandwidth at 90 GHz) polarization-sensitive correlation receivers; they expect to use the full set of sixteen 90 GHz radiometers and four 40 GHz radiometers starting in November 2003. The large telescope enables them to achieve $4'$ resolution – well suited for measuring the polarization power spectrum from where it peaks near $\ell \sim 1000$ to higher ℓ . The weather in New Jersey, however, limits observing to the winter months. They plan to observe a 1-degree patch at the North Celestial Pole using azimuth scans and expect to measure the E -mode spectrum in two winter seasons (Barkats 2003). While the sensitivity of the individual CAPMAP

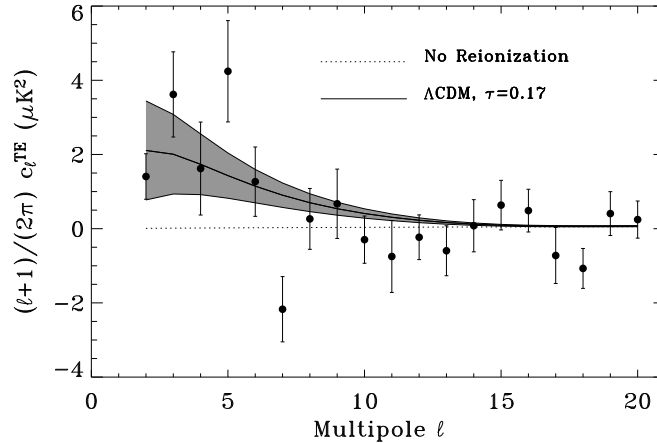


Fig. 9.— The low l portion of the polarization cross-power spectra c_l^{TE} for the WMAP one-year data (Kogut 2003). The excess power in the first few multipoles indicates significant reionization at high redshift. (Note that $(\ell + 1)/2\pi c_l^{TE}$ is plotted rather than $\ell(\ell + 1)/2\pi c_l^{TE}$.)

channels at $\sim 1mKs^{1/2}$ is roughly a factor of two to three times worse than that predicted for ground-based bolometer polarization receivers, CAPMAP is using a technique for which it has been shown that systematics can be controlled and very long integrations times are feasible.

4.1.2. balloon-borne

The current generation of balloon-borne experiments include Boomerang (Montroy et al. 2003) and MAXIPOL (Johnson et al. 2003). The Archeops balloon-borne CMB experiment has also made high frequency measurements of Galactic dust polarization over the angular scales relevant to CMB studies (Benoit et al. 2003). Boomerang made a successful Antarctic long-duration balloon (LDB) flight in 2003 January and collected 11.7 days of data. MAXIPOL had a successful 26 hour flight in 2003 May from Fort Sumner, New Mexico.

The focal plane of Boomerang was reconfigured for its 2003 LDB flight with polarization-sensitive bolometer (PSB) elements. PSBs use a micro-mesh design like the spider-web bolometer design, except that the mesh is in a square grid. The grid is metalized in only one direction to absorb only one linear polarization state of the incident radiation. A pair of PSBs is formed by using two orthogonal elements separated by $60\mu m$. A pair of PSBs can then be used with a single feed with the advantage that the pair share all the same optics, sidelobes, etc. Boomerang uses four horns to feed four PSB pairs operating at 145 GHz. In addition, there are four horns which each feed a bolometer at 245 GHz and 345 GHz to measure foreground emission from Galactic dust. For these channels, the polarization has been selected by a wire grid located in front of the horn.

At 145 GHz, the resolution is $9.5'$ and the sensitivity of order $160 \mu K_{CMBs}^{1/2}$. They observed a shallow region of 1161 square degrees and a deep region of 123 square degrees.

The MAXIMA experiment (Hanany et al. 2000) was converted to the polarimeter MAXIPOL by adding a rotating half-wave plate and fixed polarizing grids in front of the feed horns (Johnson et al. 2003). The half-wave plate spinning at two Hz causes the polarization sensitivity to be modulated at four Hz. Due to the rotating half-wave plate, all Stokes parameters are measured by each detector. While rotating half-wave plates have been used often in Galactic submillimeter observations, e.g., Hildebrand (2003), this would be the first successful implementation of the technique for CMB measurements. The MAXIPOL focal plane is cooled to $100 mK$ and by scaling the previous MAXIMA sensitivities we can expect sensitivities of order $130 \mu K_{CMBs}^{1/2}$ for each of the twelve 140 GHz channels. The beam size is $10'$ and the scan length is 2 degrees. MAXIPOL also has four 420 GHz channels to measure foreground polarization emission from Galactic dust.

The Boomerang and MAXIPOL experiments each have sufficient sensitivity to detect the E -mode polarization at intermediate angular scales; assuming the systematics are understood and controlled, the Boomerang sensitivity should allow the E -mode spectrum to be characterized beyond what has been reported by DASI.

4.2. Upcoming Experiments

4.2.1. ground-based

Two new ground-based bolometric array polarimeters are being developed: BICEP (Background Imaging of Cosmic Extragalactic Polarization, Keating et al. (2003)) and QUEST (Q and U Extra-galactic Survey Telescope, Church et al. (2003)). BICEP is scheduled to deploy to the South Pole for observations starting in Austral Winter 2005. QUEST is expected to be mounted on the DASI telescope (hereafter referred to as QUAD for QUEST and DASI) and to also start observations in Austral Winter 2005⁵.

The BICEP and QUAD experiments are in many ways companion experiments. Both exploit PSB detectors being developed at JPL and share many team members. They are also complementary in ℓ space, with BICEP targeting degree angular scales $10 < \ell < 200$ and QUAD targeting $100 < \ell < 2000$. The sensitivity of each experiment should allow the E -mode spectrum to be well characterized. Furthermore, QUAD should be able to detect the gravitational lensed B -mode spectrum. And, at degree angular scales, BICEP should be able to reach the required sensitivity either to detect the primordial gravitational wave B -mode signal, or to further constrain the inflationary energy scale, with the caveats that systematics must be controlled to unprecedented levels

⁵The QUEST radiometer and the optics, including the 2.6 meter Cassegrain reflector and secondary are funded, but at the time of this writing the proposal to NSF-OPP to deploy QUEST on DASI at the South Pole is pending.

($< 0.1\mu K$) and that foregrounds must also be understood at these levels. In any case, we are likely to learn much from these instruments about the experimental and foreground challenges that will need to be met by extremely deep future CMB polarization measurements.

BICEP will consist of an array of 48 horns feeding PSB detector pairs, half at 100 GHz and half at 150 GHz with 1.0° and 0.7° resolution, respectively. The 150 GHz detectors are expected to have an sensitivity of $280 \mu K_{CMB} s^{1/2}$. Cooled lenses form the optical system, providing a 20 degree field of view. The plan is to observe the South Celestial Pole with the optical boresight offset 5° to 25° from the zenith and rotating the entire array about the line of sight roughly once per minute. A novel ferrite Faraday modulator for each feed will be used to rotate the linear polarization.

QUAD (Church et al. 2003) consists of a radiometer similar to BICEP, but used at the Cassegrain focus of a 2.6-meter on-axis precision telescope. The secondary will be held by a low-loss foam cone as was done successfully for COMPASS (Farese et al. 2003) and CBI (Padin et al. 2002). The entire telescope will be mounted on the existing DASI mount, replacing the faceplate on which the DASI receivers and horns currently reside, as shown in Fig. 5. The QUEST focal plane consists of 12 PSB pairs at 100 GHz and 19 pairs at 150 GHz. The expected sensitivity is $300 \mu K_{CMB} s^{1/2}$ at 150 GHz with a $4'$ beam. The DASI mount is fully steerable and also can be rotated along the line of sight. The latter feature will be used along with a rotating half-wave plate to modulate the polarization response. The half-wave plate will be not be synchronously rotated as for MAXIPOL, but rather set at a fixed angle for each scan.

The Array for Microwave Background Anisotropy (AMiBA⁶) is being built for measurements of the fine-scale CMB temperature and polarization anisotropy as well as for observations of the Sunyaev-Zel'dovich Effect. The project is led by the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan and the array will be deployed to Mauna Kea, Hawaii. Like the CBI, AMiBA is an interferometric array mounted on a common platform. The specifications call for 19 elements operating at 90 GHz with full polarization capabilities and a 20 GHz correlation bandwidth. Two sets of array dishes, 1.2 meter and 0.3 meter are planned. Initial observations targeting the E -mode spectrum with a subset of the array are planned to start in 2004.

4.2.2. *satellite-based*

The Planck Surveyor⁷ (Lamarre et al. 2003) is a dedicated CMB satellite scheduled to launch in 2007 to measure the entire sky in nine frequency bands using coherent, HEMT-amplified radiometers at 30, 40 and 70 GHz and bolometric detectors at 100, 143, 217, 353, 545 and 857 GHz. While initially designed primarily for CMB temperature measurements, it has considerable polarization sensitivity. The HEMT amplifier correlation receivers are intrinsically polarized and there

⁶see <http://amiba.asiaa.sinica.edu.tw/>

⁷see <http://astro.esa.int/SA-general/Projects/Planck/>

are 4 at 30 GHz, 6 at 44 GHz and 12 at 70 GHz (Mennella et al. 2003). The resolution provided by the single 1.5 meter aplanatic primary ranges from $33'$ to $14'$ across these bands. There are four unpolarized detectors for each of the bolometer bands, providing excellent frequency coverage and resolution of $9.2'$ at 100 GHz, $7.1'$ at 143 GHz, and $5'$ at all the higher frequency bands. The prime polarization sensitivity is provided by four PSB pairs for each of the 100, 143, 217 and 353 channels. The polarization sensitivity for the resulting Planck maps is expected to be of order $4 \mu K$ per pixel for the 100 and 143 GHz maps over the entire sky. Comparing Planck to the expected state of the art for ground and balloon-borne experiments 5 years from now, is similar to comparing WMAP to existing experiments. The ground-based and balloon-borne experiments are expected to make deeper polarization maps but over much smaller regions. Planck's coverage of the entire sky is unique and valuable and its wide frequency range will be unsurpassed for understanding foregrounds. Projections for Planck's power spectrum results can be found in the excellent CMB review by Hu & Dodelson (2002).

Planck is the next generation satellite, both more ambitious and riskier than WMAP. WMAP was designed with emphasis on control of systematics and calibration even at the expense of sensitivity. There are no active coolers (or heaters) on WMAP and as a result the focal plane runs warmer than optimum. To achieve high sensitivity Planck's bolometers require active cooling. WMAP used correlation radiometers with receivers fed by completely separate telescopes pointing 140 degrees apart on the sky, providing simultaneous differencing on these scales. Planck has a single optical system and focal plane shared by coherent and bolometric radiometers. On large scales, it will be difficult to match the precision of WMAP. On small angular scales and for polarization measurements, however, the Planck sensitivity is necessary and will allow significant improvements to be made over WMAP. At these scales and sensitivities, the wide frequency coverage of Planck will also be invaluable for understanding foregrounds.

4.3. Future Experiments

The current and planned experiments will measure CMB polarization with unprecedented sensitivity. In addition, these experiments will teach us a great deal about the efficacy of new techniques and detectors, about the ability to control systematics and, of course, about astronomical foregrounds.

We are on the cusp of major advances in detector technology both in large-format bolometer arrays and in coherent detector arrays⁸. Using integrated circuit technologies it will shortly be possible to build correlation receivers on a single chip (Gaier et al. 2003); it is possible to conceive of a CAPMAP-like experiment with hundreds of radiometers. The ease of duplicating receivers can also be applied for future interferometers. Interferometers, however, will be limited by the

⁸see http://www.sofia.usra.edu/det_workshop/ for a current review of detector technology

size of broad bandwidth correlators (the correlator scales as N^2 , where N is the number of array elements). One can conceive of scaling the DASI and CBI design (Padin et al. 2001) for ~ 100 receivers, but much larger correlators will require further advances in correlator technology.

Large format arrays for bolometers are now possible using both “pop-up” arrays developed at NASA/GSFC (e.g., Dowell et al. 2003) and monolithic arrays developed at Caltech/JPL (e.g., Glenn et al. 2003). The current push in bolometer array technology is directed at micro-machined planar arrays with superconducting transition-edge sensors (TES) with multiplexed readouts. Current arrays of order 1000 channels are being developed and much larger arrays will be possible with this technology. The next step being actively pursued is large format arrays of superconducting microstrip, antenna-coupled bolometer detectors (e.g., Goldin et al. 2003). The antenna-coupled technology offers great flexibility; the elements can be configured for dual polarization and support several frequency channels.

New telescopes are required to take advantage of the new bolometer arrays and at least three are in various stages of planning. The South Pole Telescope (SPT)⁹ is an 8-meter, precision, off-axis telescope funded by NSF-OPP to be deployed to the South Pole station in late 2006 and equipped with a 1000-element bolometric radiometer. A large focal plane polarimeter is planned for the SPT, but is not currently funded.

Planning is underway for the Atacama Cosmology Telescope (ACT Kosowsky 2003), a 6 meter off-axis telescope planned for Chile which could also be equipped with a polarimeter. Finally, planning is also underway for Polarbear, a 3 meter off-axis telescope dedicated to CMB polarization measurements with a large array (1000 to 3000 elements) of polarization-sensitive antenna-coupled bolometers (Tran 2003).

The most ambitious plan on the horizon is for a dedicated CMB polarization satellite to conduct the definitive search, i.e., foreground-limited, for the signature of inflationary gravitational waves in the CMB, i.e., to measure the gravitational wave B -mode spectrum. It is the goal of the Inflation Probe of NASA’s *Beyond Einstein* program¹⁰. NASA plans to fund of order three studies toward the eventual launch of a \$350M to \$500M Inflation Probe.

5. Conclusions

The detection of CMB polarization marks the beginning of a new era in CMB measurements and for cosmology. With the first detection of E -modes and the TE correlation, the standard model has passed a critical test, and already the large-angle TE correlation is pointing the way

⁹Collaboration led by the University of Chicago and including the University of California, Berkeley, Case Western Reserve University, University of Illinois at Urbana and the Smithsonian Astrophysical Observatory

¹⁰<http://universe.gsfc.nasa.gov/>

to a revised understanding of the reionization history of the universe.

Polarization measurements are now at a turning point reached by temperature anisotropy measurements a decade ago, when they were first detected by COBE and FIRS (Smoot et al. 1992; Ganga et al. 1993); as was the case with the temperature measurements, we can count on rapid progress in the characterization of the CMB polarization. The *E*-mode spectrum should be well measured by ground-based and balloon-borne experiments, and the *Planck Surveyor* satellite over the next several years. A few experiments now underway should already be capable of measuring the gravitationally lensed *B*-mode spectrum, and possibly even the gravitational wave *B*-mode spectrum.

It is unreasonable, however, to expect that increased instrument sensitivity alone will allow the detection of these extremely weak signals. At the required sensitivity levels, systematics will be much harder to control and contamination from astronomical foregrounds will be much more severe. The need for several independent experiments using different techniques including ground, balloon and eventually satellite-based instruments is even more important than it was for the temperature CMB measurements. Continued exploratory work with new techniques and with ever more sensitive detectors is necessary to ensure the eventual success of NASA’s Inflation Probe.

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